$$\begin{pmatrix}\Delta y_D \\ \Delta x_B\end{pmatrix} = G\begin{pmatrix}\Delta L \\ \Delta V\end{pmatrix} + G_{d1}\begin{pmatrix}\Delta F \\ \Delta z\end{pmatrix} = G(I + F_{DB}M)^{-1}\begin{pmatrix}\Delta u_{c1} \\ \Delta u_{c2}\end{pmatrix} + [G_{d1} - G(I + F_{DB}M)^{-1}F_{DB}N]\begin{pmatrix}\Delta F \\ \Delta z\end{pmatrix} \quad (62)$$

where G and G_{d1} are given by eqs 41 and 42, respectively. To make the steady-state disturbance gains zero, the inferential feed-forward controller can be calculated as

$$F_{DB} = G(0)^{-1}G_{d1}(0)[N - MG(0)^{-1}G_{d1}(0)]^{-1} \quad (63)$$

For the column studied here, this becomes

$$F_{DB} = -\begin{pmatrix}0.2713 & 0.1352 \\ 0.6950 & 0.1689\end{pmatrix} \quad (64)$$

This inferential feed-forward controller is also used in conjunction with an IMC controller tuned by optimizing the robust control performance. The controller parameters are given in Table 4. This inferential feed-forward controller was tested under the sequence of disturbances shown in Figure 10 at the two operating conditions (95%, 5%) and (93%, 6%). The control performance results are shown in Figures 12 and 14, and the corresponding sums of squared control errors are given in Table 5. The sums of squared control errors for the cases with measurement noise are given in Table 6. Figure 17 shows the set-point tracking performance with the sum of squared control errors given in Table 7. From Figures 12 and 14 and Tables 5 and 6, it can be seen that F_{DB} can also offer very good control performance in disturbance rejection, particularly for feed rate disturbances. This is because F_{DB} is designed for rejecting both feed composition and feed rate disturbances. Compared to the inferential feed-forward controllers using tray temperatures, the control system with F_{DB} exhibits better control performance in disturbance rejection. This confirms the robustness analysis results shown in Table 4. Tables 5 and 6 show that the control performance with F_{DB} is insensitive to measurement noise. This is because tray temperature measurements are not used in F_{DB}, and thus, the control performance is affected only by composition measurement noise. Figure 17 and Table 7 show that the control system with F_{DB} has better set-point tracking performance for the top product composition than the control system without inferential feed-forward control, but the same is not true for the bottom product. It should be emphasized here that the inferential feed-forward control is designed for the rejection of unmeasured disturbances.

4. Conclusions

Two inferential feed-forward control strategies are proposed. One uses uncontrolled secondary process variables, whereas the other uses the manipulated variables for the controlled secondary process variables with fast dynamics. These strategies are useful when disturbances cannot easily be measured and, hence, direct feed-forward control cannot be applied. The effects of disturbances on the primary process variables are inferred from certain easily available measurements of uncontrolled secondary process variables or from the manipulated variables for certain controlled secondary process variables with fast dynamics. The main advantage of such inferential feed-forward control strategies is that measurements of disturbances are not needed. A robustness analysis is presented, and it is shown that robustness is an important factor to be considered when selecting secondary process variables. Secondary process variable selection and feedback controller tuning can be performed by optimizing the achievable robust control performance represented by the structured singular value of the overall control system.

The proposed strategies have been applied to a simulated methanol−water separation column. Nonlinear dynamic simulations demonstrate that the proposed strategies can significantly improve the disturbance rejection capabilities of the distillation composition control system. Robustness analysis shows that using multiple tray temperature measurements can significantly improve the robustness of the control scheme, which is confirmed by simulations.

The present work considers only static inferential feed-forward controllers aimed at removing the steady-state effects of disturbances on the controlled variables. Extension to dynamic inferential feed-forward control is currently under study and will be reported in the future.

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Literature Cited

(1) Brosilow, C.; Joseph, B. *Techniques of Model-Based Control*; Prentice Hall PTR: New Jersey, 2002.

(2) Ogunnaike, B, A.; Ray, W. H. *Process Dynamics, Modeling, and Control*; Oxford University Press: New York, 1994.

(3) Shinskey, F. G. *Process Control Systems*; McGraw-Hill: New York, 1979.

(4) Yu, C. C. Design of Parallel Cascade Control for Disturbance Rejection. *AIChE J.* **1988**, *34*, 1833−1838.

(5) Shen, S. H.; Yu, C. C. Selection of Secondary Measurement for Parallel Cascade Control. *AIChE J.* **1990**, *36*, 1267−1271.

(6) Shen, S. H.; Yu, C. C. Indirect Feed Forward Control: Multivariable Systems. *Chem. Eng. Sci.* **1992**, *47*, 3085−3097.

(7) McAvoy, T. J.; Ye, N.; Chen, G. Nonlinear Inferential Parallel Cascade Control. *Ind. Eng. Chem. Res.* **1996**, *35*, 130−137.

(8) Brosilow, C.; Joseph, B. Inferential Control of Processes. *AIChE J.* **1978**, *24*, 485−509.

(9) Guilandoust, M. T.; Morris, A. J.; Tham, M. T. Adaptive Estimation Algorithm for Inferential Control. *Ind. Eng. Chem. Res.* **1988**, *27*, 1658−1664.

(10) Budman, H. M.; Webb, C.; Hocomb, T. R.; Morari, M. Robust Inferential Control for a Packed-Bed Reactor. *Ind. Eng. Chem. Res.* **1992**, *31*, 1665−1679.

(11) Lee, J. H.; Morari, M. Robust Inferential Control of Multi-Rate Sampled-Data Systems. *Chem. Eng. Sci.* **1992**, *47*, 865−885.

(12) Strang, G. *Linear Algebra and Its Applications*, 2nd ed.; Academic Press: New York, 1980.

(13) Doyel, J. Analysis of Feedback Systems with Structured Uncertainties. *IEE Proc. Pt. D, Control Theory Appl.* **1982**, *129*, 242−250.

(14) Doyel, J. Structured Uncertainty in Control System Design. In *Proceedings of the IEEE Conference on Decision and Control*; IEEE Press: Piscataway, NJ, 1985; pp 260−265.

(15) Luyben, W. L. Simple Method for Tuning SISO Controllers in Multivariable Systems. *Ind. Eng. Chem. Process Des. Dev*. **1986**, *25*, 654−660.

(16) Tham, M. T.; Vagi, F.; Morris, A. J.; Wood, R. K. Online Multivariable Adaptive Control of a Binary Distillation Column. *Can. J. Chem. Eng.* **1991**, *69*, 997−1009.

(17) Tham, M. T.; Vagi, F.; Morris, A. J.; Wood, R. K. Multivariable and Multirate Self-Tuning Control—A Distillation Column Case Study. *IEE Proc. Pt. D, Control Theory Appl.* **1991**, *138*, 9−24.

(18) Skogestad, S.; Lundstrom, P. MU-Optimal LV Control of Distillation Columns. *Comput. Chem. Eng.* **1990**, *14*, 401−413.

(19) Zhang, J.; Tham, M. T.; Morris, A. J. High Performance Distillation Column Control through Novel Control Configurations. In *Proceedings of IFAC DYCORD+95*; Pergamon Press Ltd.: Oxford, U.K., 1995; pp 93−98.

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